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The following communication was read:—

On Craters of Denudation, with Observations on the Structure and Growth of Volcanic Cones. By Sir CHARLES LYELL, Pres. Geol. Soc.

IN the first edition of my 'Principles of Geology,' published in 1830 (vol. i. ch. 30), I explained the grounds of my objection to the theory previously advanced by Baron von Buch to account for the origin of the Caldera of Palma, the Gulf of Santorin, and other bowl-shaped cavities of large dimensions, for which he proposed the name of "Craters of Elevation." I regarded the circular escarpments surrounding these vast cavities as the remnants of cones of eruption, the central parts of which had been destroyed, and I conceived that the removing cause had been chiefly, if not wholly, engulfment.

In the second edition of my 'Principles,' published in 1832, or two years later, I discussed more particularly the origin of the single deep gorge, which in Palma, Barren Island, and other so-called elevation-craters, forms a breach in the circular range of cliffs, surrounding the central cavity. This ravine or narrow passage I attributed "to the action of the tide during the gradual emergence from the sea and upheaval of a volcanic island" (ch. 22. vol. i. p. 452), and I at the

Fig. 1.—*View of the Isle of Palma, and of the entrance into the central cavity or Caldera.—From Von Buch's "Canary Islands."*

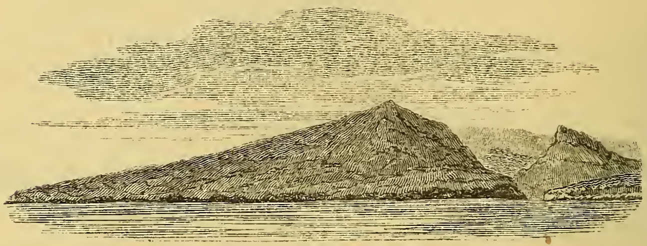


Fig. 2.—*Map of the Caldera of Palma and the great ravine, called "Baranco de las Angustias."—From a Survey of Capt. Vidal, R.N.*, 1837.

same time alluded to its analogy to the single passage leading into the lagoons of many annular coral islands or Atolls.

Although I then distinctly announced this theory in regard to such narrow ravines, the idea had not occurred to me that the same denuding power of the waves and tides, which were thus appealed to as adequate to remove the rocks once filling such deep gorges, must of necessity have exerted a like action on the walls of the craters themselves. I well knew from the excellent description published by Von Buch of Palma, an island to which I specially alluded, that the long and deep chasm called Baranco de las Angustias, which alone breaks the continuity of the rocks enclosing the caldera, and was bordered on both sides by steep cliffs, was not less than between six and seven miles in length, being at its upper extremity 2000 feet or more in depth. I ought therefore, in consistency, to have inferred, that the same ocean, which I supposed to have stood successively at various levels, and in the course of ages to have ground down and carried away so vast a volume of rock, from this channel, must during the same long period have excavated a part of the hollow once occupied by similar and equally destructible materials.

By referring to the annexed map, fig. 2, from Capt. Vidal's 'Survey of Palma,' the reader will observe that the sea cliff at Point Juan Graje, 780 feet high, now forming the coast at the entrance of the great ravine, is continuous with an inland cliff which bounds the same ravine on its north-western side. No one will dispute that the precipice at the base of which the waves are now beating, owes its origin to the undermining power of the sea. It is natural therefore to attribute the extension of the same cliff to the former action of the waves exerted at a time when the relative levels of the island and the ocean were different from what they are now.

Of late, after fully reconsidering the subject, I have come to the conclusion that the origin of a great part of the Caldera of Palma was probably due to denudation, and that the same holds true of other analogous cavities, such as are seen in Teneriffe, and many volcanic islands, so well described by M. von Buch in his classical work on the Canaries. Santorin in particular, which has been selected as furnishing the best type of a crater of elevation, owes, I believe, the chief part of the extension of its circular gulf to denudation, the whole crater together with the surrounding rocky islands having subsided bodily since the denudation, so as to be now half submerged in the waters of the Mediterranean.

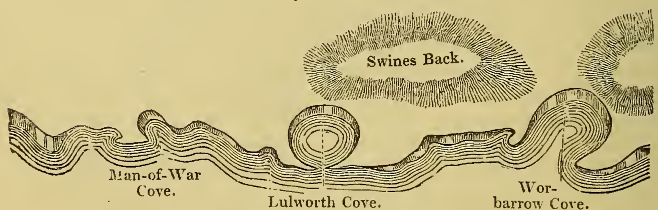
Before I proceed to treat more in detail of this and other volcanos, I shall offer a few preliminary remarks, to prepare the geologist for the reception of the views about to be proposed. In the first place it is admitted, that many of the volcanos, in which these large crateriform hollows exist, have been formed wholly or in part beneath the level of the sea; 2ndly, the quantity of solid rock assumed by me to have been worn down and carried away through a narrow channel by the waves and currents (as the islands emerged) is by no means great, when contrasted with the masses removed from many elliptical areas, which have been called valleys of elevation, such as the Wealden, or

the smaller valley of Woolhope. The latter has been described by Sir R. Murchison, and more recently by Mr. Phillips*. It is $4\frac{1}{2}$ miles in diameter, and resembles in size as well as in some of its leading features the Caldera of Palma, the beds, in the boundary cliffs encircling the excavated space, dipping in all directions outwards, and the cliffs for that reason retaining more easily their steepness or verticality.

3rdly. If the crater of a submarine volcano be upraised and begin to emerge, the sea will still flow into it on its lowest side, and the circular basin will then be filled and emptied alternately by the flux and reflux of the tide, or by the rise of water blown into the opening by prevailing winds, and then falling again as soon as this force ceases to act, by which means a passage will be kept open, the crater being scoured out like estuaries which have narrow entrances. On the efficacy of this last mode of aqueous erosion I must particularly insist, as it aids us more than any other in comprehending the theory of denudation-craters. The Basin of Mines in the Bay of Fundy illustrates the manner in which a large bay, communicating with the ocean by a narrow strait, may be filled and half-emptied every tide, so that the waves and currents may sweep out in the course of centuries a vast volume of mud and sand, and produce on all sides of the bay long ranges of cliffs annually undermined, several hundred feet perpendicular, some composed of soft red marl, others of hard quartzose grit, and others of columnar basalt. The Bay of Fundy it is true would not present, if it were upraised and laid dry, so circular a hollow as the so-called crater of elevation, but there are numerous coves on a part of the coast of Dorsetshire which are as perfectly circular, if not more so than the Gulf of Santorin or the Caldera of Palma, and in which the single breach effected by the sea on one side is not larger in proportion to the entire girdle of encircling cliffs. These cliffs moreover, which every geologist attributes exclusively to the denuding action of the sea, are precipitous, and most lofty at the head of the bay or farthest from the entrance, where they consist of inclined strata of chalk. Lulworth Cove, which is 1300 feet across, is the most perfect example (see fig. 3). In this case the hardness of

Fig. 3.

Coast of Dorsetshire.



* Murchison, Silurian System, Part I. p. 428, and J. Phillips, Mem. of Geol. Survey, vol. ii. p. 167.

the Purbeck and Portland strata prevents the waves and tides from breaking down and widening the seaward barrier, and the comparative softness of the vertical or highly inclined beds between the barrier and the chalk at the head of the bay promotes the enlargement inside the entrance.

4thly. But there are certain valleys in Australia, described by Mr. Darwin, which from their depth, the steepness of their boundary cliffs, and the narrow gorges by which the sea has entered to hollow them out, afford perhaps a still more striking explanation of the mode of operation, to which I shall refer in great part the origin of such craters as Palma, the Gulf of Santorin, and others of similar large dimensions. I allude to those valleys near Sydney in New South Wales, by which the great platform of sandstone, 1200 feet thick, is penetrated. The traveller, says Mr. Darwin, when walking over the summit plains, finds himself suddenly at the brink of a continuous line of lofty cliffs, so perpendicular, that he can strike with a stone the trees growing at the depth of between 1000 and 1500 feet below him. At the distance of several miles he beholds the opposite line of cliff, rising up to the same height with that on which he stands, and formed of the same horizontal strata of sandstone. So continuous are the bounding lines of cliff, that to descend into some of these valleys it is necessary to go round twenty miles; but what is still more remarkable, these valleys, although several miles wide in their upper parts, generally contract towards their mouths to a mere chasm, impassable to man or beast. Thus the gorge of the Cox river is only 2200 yards wide, and about 1000 feet in depth. Mr. Darwin at first asked himself whether the mass of stone removed from these great amphitheatrical depressions, had not subsided vertically; but was compelled to abandon this notion on considering the narrow promontories which projected from the platforms into the valley. He was also struck with the resemblance of the inland basins or bay-like recesses to the present bold sea-coast, where there are similar recesses forming fine harbours, connected with the sea by narrow mouths, sometimes not more than a quarter of a mile in width, the cliffs being formed of similar sandstone.

5thly. It must also be remembered that in the coasts of volcanic islands, such as Palma, Santorin, St. Helena, and others, there are lofty cliffs of basaltic and other igneous rocks, often traversed by dikes which have been formed by the undermining action of the sea, and are still wasting away. Mr. Darwin has particularly dwelt on the enormous cubic mass of hard rock pared off by the swell of the Atlantic from the coasts of St. Helena, where there are perpendicular cliffs from 1000 to 2000 feet in height, consisting of basaltic strata traversed by dikes (p. 91). In this island also, as well as in St. Jago and Mauritius, he has observed in his volume on Volcanic Islands, p. 93, that the ring of basaltic mountains forming what is commonly called "the crater of elevation," must once have been nearly or quite continuous, although now broken. Some very wide breaches have, he observes, been evidently effected by the denuding action of the waves. All these islands, he concludes, have been elevated in mass.

It will be seen therefore that to account for the excavation of certain large crateriform cavities in some of these same islands, I am merely introducing a force, which is already acknowledged to have been most energetically exerted in destroying extensive masses of rock formerly environing the spaces called elevation-craters.

Having said thus much of the denuding or removing power, I shall next offer a few prefatory remarks on the mode of origin of the dome-shaped volcanic masses, of which I consider the boundary rocks of every denudation-crater to be the basal remains. Mr. Scrope, writing in 1827, attributed the formation of a volcanic cone chiefly to matter ejected from a central orifice, but partly to the injection of lava into dikes, and to that force of gaseous expansion, the intensity of which in the central parts of the cone is attested, he said, by the local earthquakes which often accompany eruptions*. But it was reserved for M. E. de Beaumont, seven years later, to point out that the extent, uniform thickness, and compact structure of many sheets of basaltic lava, which constitute the flanks of many volcanic cones, such as Etna and Somma, leave very little doubt that they were originally poured out on a surface, much less inclined to the horizon than the angle at which they now slope. To the same observer we are indebted for most valuable researches into the laws governing the flow of lava streams, the result of which he published after his visit to Etna in 1834. In his memoir on that mountain he endeavoured to prove that the numerous up-filled fissures or dikes are the evidence and measure of the elevation of the distended volcanic mass, consisting of sheets of lava and alternating conglomerates, and that the whole mountain is probably undergoing upheaval bodily from time to time, as often as it is traversed by star-shaped cracks, such as occurred during the eruption of 1832.

In the later edition of my 'Principles†' I referred to the labours of M. de Beaumont, and admitted that a greater part of the beds exposed in the precipices of the Val del Bove were "originally less inclined, some of them perhaps much less so than now." At the same time I attributed the change of position to the "successive fracturing, distension and upheaval of the cone," not to a sudden upthrow. Whether I still underrated the amount of unequal elevation by which certain beds are believed to have been tilted and changed from their pristine horizontality, I know not, but I feel as convinced as ever that I was right in continuing to reject the hypothesis of elevation-craters, of which MM. de Beaumont and Dufresnoy have been the able and strenuous advocates. When repeating in my different publications the objections previously urged by myself and others to the theory of Von Buch, I always cited the argument so strongly insisted upon by M. Constant Prévost, that if beds of non-elastic materials had yielded suddenly to a violent pressure directed from below upwards, we should not find a circular cavity with an even and unbroken rim, but an irregular opening where many rents converged, and these rents

* Geological Transactions, 2nd Series, vol. ii. p. 341.
† See edition of 1847, p. 401.

would now be seen breaking through the walls of the crater, and widening as they approached the empty central space*. Instead of any such open rents being visible in the walls of the Caldera of Palma, and in analogous crateriform cavities, we invariably find dikes or upfilled fissures, in which, as well as in tortuous veins, often forming a reticulated mass, the melted matter was clearly consolidated before the boundary cliffs were formed. The origin therefore of all such rents, numerous as they are, was wholly antecedent in date to the whole movement assumed as the cause of the elevation-crater. I have also in every edition of my works uniformly contended, in common with Messrs. Scrope, C. Prévost, and others, that in mountains like Etna, Mont Dor, and the Cantal, we must look to that area where we now find the greatest thickness of lava and fragmentary ejections as the chief and permanent source of the alternating lavas, tuffs, scoriæ, and conglomerates composing the volcanic cone. The increase of the cone, so far as it consists of such superimposed igneous products, I compared to the exogenous growth of a tree, and in Etna and some other volcanos a series of superimposed sloping beds has been piled up successively to a thickness of more than 4000 feet. We may call the injection of lava, and the distension and upheaval caused by the hydrostatic action of imprisoned vapours, to which M. de Beaumont has justly attributed much greater importance than I had previously conceded, or even than Mr. Scrope had assumed, the *endogenous* growth of the mountain. The intensity of this last-mentioned mode of increase is much greater in the more central than in the marginal parts of a volcano. For this reason we perceive near the margin or base of the cone that the lava and beds of scoriæ, as they gradually thin out, become intersected by fewer and fewer dikes, until these at length entirely cease to appear. Not only the number, but the size or width also of such dikes may often be seen to augment as we approach nearer and nearer to the central axis of the cone. Other generalizations on the origin and growth of cones and craters I shall defer to the sequel, as they will be best explained when I am commenting on the structure and probable mode of formation of particular volcanos.

Palma.

To one of the most remarkable of these, the island of Palma, I shall first allude. Von Buch has given us a graphic picture of what seems to be the most splendid and perfect example yet discovered of a huge and deep cavity, surrounded on all sides by a circular range of precipices which are 4000 feet in height, the beds dipping outwards in all directions from the centre of the void space, which is about six geographical miles in diameter. The sloping beds consist chiefly of basalt alternating with conglomerates, composed in part of *rolled* masses of similar basalt. Here, therefore, we seem to have evidence of the subaqueous origin of a portion at least of the volcanic accumulation, while the highest part of the cone may have raised

* Principles of Geology, ch. 24. Mém. de la Soc. Géol. de France, tome ii. p. 91.

itself, like Stromboli, and been exposed to the power of the waves. The inclination of the beds corresponds to that of the external slope of the island, being greatest towards the central hollow axis, and less steep near the sea. The intersecting dikes and veins are more and more abundant as we approach the crater, and therefore are most numerous where the slope of the beds is greatest. This is seen by aid of a transverse section of the entire succession of beds obtained in the cliffs bounding the one deep baranco which extends from the sea-coast to the crater. The origin of this deep ravine, a phænomenon, says Von Buch, common to all "craters of elevation," and which recurs in the Great Canary, the island of Amsterdam, Barren Island, and, as we shall presently see, in Santorin, is left wholly unexplained by the hypothesis of sudden upheaval, unless we are prepared to assume that the same engulfment which swallowed up the central mass once filling what is now the hollow axis of the cone, has extended to one side and one side only of the encircling zone of rock (see figs. 1 & 2, p. 208). Had there been several such gorges interrupting the circular and solid girdle which encloses the caldera, it might have been argued with some plausibility that such openings were due to the fracture of a non-elastic mass, which, however slowly upraised, could not expand and stretch, because even the less compact beds were fortified by ribs of the unyielding stony substances constituting the dikes.

According to Von Buch, the mass upheaved in Palma fell back into the middle of the crater *, but sections seem wanting to show that the nature and structure of the bottom of the great hollow, where the ground rises very considerably in the centre of the caldera, are such as to lend countenance to this conjecture. The theory of denudation briefly stated at the commencement of this paper may explain not only the excavation of the caldera, but may account for its enormous size; and what is still more satisfactory, it absolutely requires the existence of a great baranco through which the abstracted rocky materials or the missing portions of the cone have been swept out in the form of mud, sand and gravel. To refer the evacuation of the Caldera of Palma to explosion is inadmissible, for the same reason that M. de Beaumont has very properly rejected a similar hypothesis in regard to the Val del Bove on Etna, viz. because if so vast a volume of solid matter had been blown out into the air, it must when it fell down again have formed a dense bed of fine dust and angular fragments of stone, such as does not envelope the surface or exterior slope of the island. Sections of such an envelope would have been seen in the ravines or barancos, some of them 500 feet deep, which radiate towards all points of the compass, from the rim of the caldera to the sea, without however interrupting by their upper or shallower extremities the continuity of that rim. As to the origin of these numerous barancos, M. von Buch is of opinion, that the torrents now flowing in some of them, even when the snow melts in the higher parts of the truncated cone, are too inconsiderable to cause them. He sup-

* Description des îles Canaries, p. 285. French edition, 1836.

poses them to have been produced when the island was suddenly upraised, an hypothesis which I regard as inadmissible, because they never intersect the rim of the escarpment. If on other grounds we conclude that the elevation of Palma from the sea was gradual, we are bound to reflect whether the waves may not have contributed as well as torrents acting on rocks of unequal hardness to produce such ravines.

Santorin.

After I had indulged in the above speculations in respect to the origin of the Caldera of Palma, it occurred to me that the circular gulf or crater of Santorin offered a serious objection to the theory of denudation, because the boundary cliffs of the Gulf plunge suddenly into very deep water. It is clear that while the land and sea stand at their present relative levels, the bottom of a crater 1000 feet deep could never have been hollowed out by the denuding force of waves and currents: but learning from my friend Capt. W. H. Smyth, that a new survey of Santorin had been recently executed, under the direction of Capt. Graves, I obtained, through the kindness of Capt. Becher, of the Hydrographical department of the Admiralty, an unpublished chart, in which the soundings around and between this group of islands are laid down with great minuteness. Capt. Smyth also allowed me to consult a paper recently communicated to the Geographical Society by Lieut. Leycester, who has been actively engaged, together with Lieut. Mansell, in the late survey. From these sources I have derived data by which it will appear that the case of Santorin, so far from militating against, is, on the contrary, strongly confirmatory of the denudation theory, besides throwing no small light on the mode in which new volcanic mountains are gradually formed in the centres of many craters of denudation. The largest of the three islands surrounding the circular gulf of Santorin is called by Lieut. Leycester, Thera (see Map, fig. 4). It is of a horse-shoe form, and has an external coast-line of eighteen miles. It is three miles wide from east to west, and, as MM. Boblaye and Virlet ascertained, consists of volcanic matter, with the exception of its southern part, where Mount St. Elias (fig. 4, D), 1887 feet high, occurs, being composed of limestone and argillaceous schist. The volcanic mass is quite independent of these older formations, and abuts against them. It is made up of alternating beds of trachytic lava, tuff, and conglomerate, which, as M. Virlet has shown, have a gentle dip outwards from the centre of the Gulf, towards which they terminate abruptly in a steep and often perpendicular cliff. That these beds, and similar ones occurring in the other two eastern islands, Therasia and Aspronisi, are the lower portions of a great cone or flattened dome, the centre of which has disappeared, was the opinion arrived at by MM. Virlet and Boblaye, in the French 'Expedition of the Morea.' In the cliffs, says M. Virlet, the separate masses of trachyte and obsidian are seen to mould themselves into the inequalities of previously existing surfaces formed by fragmentary and conglomerate beds. Neither the solid nor the incoherent masses constitute wide-spreading sheets, but are dis-

Map of Santorin in the Grecian Archipelago, from a Survey in 1848, by Capt. Graves, R.N. The soundings are given in fathoms.

Fig. 4.

A. Shoal formed by submarine volcanic eruption in 1650.
B. Northern entrance.
C. Mansell's Rock.
D. Mount St. Elias, 1887 feet high.

Fig. 5.—*Section of Santorin, in a N.E. and S.W. direction, from Thera through the Kaimenis to Aspronisi.*

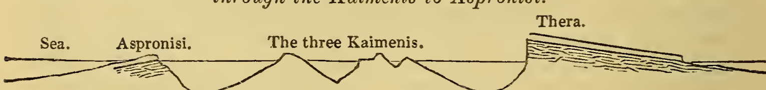
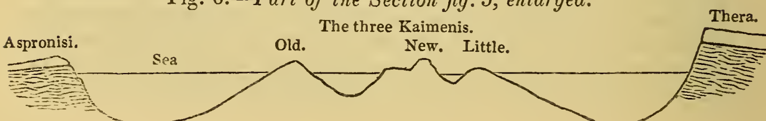


Fig. 6.—*Part of the Section fig. 5, enlarged.*



continuous and dove-tailed into each other, except one grand deposit of white tufaceous conglomerate, which forms the capping of all the islands. M. Virlet found that the vesicles or pores of the beds of trachyte were lengthened in the several directions in which they would naturally be drawn out, had they flowed as melted matter towards different points of the compass from the summit of a cone, the axis of which once occupied the centre of the gulf. From the structure, irregularity, and interrupted nature of the beds, and their moderate dip, not exceeding in Thera three or four degrees, there seems no reason to assume that they have undergone any change from their original position, except such as may have arisen from general upward and downward movements of the whole island.

The length of the outer coast-line of the three islands taken together is about thirty miles. Aspronisi is not more than a mile in circuit, and only 300 feet high. It is surrounded by dangerous shoals for a distance of about a third of a mile, as if it had recently wasted away by the action of the sea; and in the geological chapter before cited of the 'Expedition of the Morea,' it is stated that the waves are constantly preying on the marginal cliffs of the three islands, so as to enlarge the intervals between them *. That these islands were once united has been the conclusion of every geographer and geologist who has seen them; but the late survey by Capt. Graves may be said to have set the question for ever at rest. The subaqueous rim of the crater has been traced, first from Cape Acrotiri in Thera to Aspronisi, the depth of water varying from five to ten fathoms, and then from Aspronisi to Therasia, where there is the same depth, one spot, called Mansell's shoals (fig. 4, C), being no more than nine feet under water.

Throughout the circuit of these two lines of shoal, constituting the unbroken subaqueous rim of the crater, the water was found to deepen suddenly on the inside, or towards the gulf; but in the third channel, called the northern entrance (fig. 4, B), about a mile wide, between Therasia and the nearest part of Thera, a remarkable breach is discovered in the continuity of the submarine walls of the great bowl. Near the land on both sides the water is shallow for a certain distance, as if the cliffs had wasted away. Then there is a plunge to 100 fathoms, and in the middle of the passage no less than 195 fathoms, or 1170 feet. This deep ravine in the bed of the sea is significantly spoken of by Lieut. Leycester, as the "door into the crater." It is evidently the "portillo" of Santorin, or its "Baranco de las angustias." It is the single chasm through which, when the Santorin archipelago stood more than 1000 feet higher, the contents of the vast crater of denudation were swept by the sea; and it is a remarkable fact, that its depth precisely agrees, to within a few inches, with the greatest depth discovered, after minute soundings, in any part of the gulf. It is also important to remark, that outside the islands, where the soundings deepen much more gradually than in the inside of the gulf, they reach in some places, as for example about two miles south-west of Aspronisi, to depths of 250 and 260 fathoms, showing that the Gulf

* Expédition de Morée, vol. ii. p. 259.

of Santorin, deep as it is, is still shallower than some of the adjoining parts of the Mediterranean, and might, if upraised, present a dry crater connecting by a chasm with the sea.

The greatest depth of the crater or gulf according to the late survey was found to be between the shores that are highest; that is to say, between that part of Thera where Merivali is situated and the opposite cliffs of Therasia, which are about four miles distant. Here the soundings reached 213 fathoms. The height of the escarpment at Merivali is 1171 feet, that of the high land in Therasia 936 feet, the cliffs on both sides above water and below being very steep and in great part perpendicular. If therefore, says Lieut. Leycester, the crater were empty, the observer looking down into it from Merivali would behold a frightful abyss 2449 feet in depth, the bottom consisting generally of reddish or brownish clay, and the opposite side, or that of Therasia, would be only 235 feet less deep. A vast circular cavity, nowhere less than 1200 feet deep, would be seen to be eighteen miles in circumference, the encircling cliffs broken in one place, and one only, by a ravine 1170 feet deep. The walls of the great crater would be nearly twice as high on the north-east as on the south-west side, on the whole very uniform in outline; but at Scaurus a narrow promontory would jut out from the steep cliff, about one-third of a mile into the gulf.

In the middle of this great caldera (the waters being drawn off) a single volcanic mountain would appear, bearing the same relation to the surrounding deep sea and circular escarpment which the Peak of Teneriffe bears to its moat and bastion, as described by Von Buch, or which the active volcano in the centre of Barren Island bears to the marine channel and outer girdle of rocks by which it is surrounded. This central mountain (see sections figs. 5 & 6, p. 216) is about five miles and a half in circumference at its base, and is surrounded on all sides by deep water. Its longest diameter is about two miles, in a direction from north-east to south-west. It has five summits, which spring from a ridge at the height of about 1000 feet from the bottom of the crater. Three of these summits, called the Kaimenis, rear their heads above the present level of the waters. The north-eastern, called the Little Kaimeni, or little burnt island, is 222 feet above water, formed by eruption in 1753. There is a cone on it having a crater eighty feet deep, and on the north side of it a considerable bank, of large blocks of lava and ashes. The top of this cone is 1550 feet above the base of the mountain. The middle, or New Kaimeni, was produced during eruptions in 1707 and 1709. It was composed at first of two parts, which were afterwards united. Its summit consists of a cone, which rises 351 feet above water. Its sides slope at an angle of 33°, and its shape, well delineated by Bory St. Vincent in plate 37. fig. 2 of the Morea Expedition, is precisely that of cones of single eruption in Auvergne, or on the flanks of Etna. The crater on the summit is eighty yards in diameter, according to Lieut. Leycester, and the highest point of the cone is 1629 feet above the bottom of the abyss. The south-western island, or the Old Kaimeni, is 328 feet above water, or twenty-three feet lower than the highest of the other peaks. The channel which

separates it from the New Kaimeni is in one part 100 fathoms deep. The two other summits spoken of are submerged cones, one occurring on the north and the other on the east of the Kaimenis, the northern peak being twenty-four fathoms under water and 1158 feet high, the eastern peak twenty fathoms, giving it a height of 1251 feet above the bottom of the crater. Their summits are flat. They spring from the same ridge as the Kaimenis, and the whole mountain with its five summits nearly bisects the gulf in a north-east and south-west direction, a direction not assigned to the Kaimenis in maps published previously to the late survey (see Map, fig. 4. p. 216).

From a history of the successive formation of different parts of this central volcano, or volcanic ridge, we derive the knowledge of facts of great geological importance, for we are taught that the Kaimenis owe their present elevation not only to the heaping up of cones of fragmentary matter, but to the bodily though partial upheaval of portions of the trachytic mass, bearing on its surface a thin layer of pumiceous ash, containing marine shells. The rise of this bed of pumice, first called the White Island, in the year 1707, is on record, and it has been examined of late years by Mr. Edward Forbes, who made a collection of the marine shells contained in it, among which were both univalves and bivalves, of the genera *Pectunculus*, *Arca*, *Cardita*, *Trochus*, and many others, all recent species of the Mediterranean *, in a fine state of preservation, and implying that the sea-bottom on which they lived, when enveloped by a fall of ashes, was between twenty and thirty-five fathoms in depth. The state of the bivalves, their shells double with their valves closed, with the epidermis remaining, indicated that they had been suddenly destroyed. We know therefore from the habits of these mollusca, as observed by Mr. Forbes in the Mediterranean, that an upheaval of at least 220 feet was required to bring them up to the level of the sea, above which they now rise to the height of five or six feet. This bodily upheaval of a certain mass of ashes does not appear to have affected the other two islands equally, if at all, at the same period, still less to have extended to the outer islands; for if so, such ports as Phira, built on the water's edge, on a talus of fallen fragments from the vertical cliff, would have been carried upwards. We have here then an indisputable proof, in the Gulf of Santorin, that in the gradual reconstruction of a volcanic mountain in what was previously the original centre of eruption, large masses of solid matter may be lifted up in mass, 150 or 200 feet, and sustained at that height, while other parts of the volcano in the immediate vicinity do not participate in the movement. This power of the lava or gases to carry upwards, to a height of 200 feet or more, a stratified deposit, which M. Virlet considered as having floated like cork on the top of a denser fluid, is a phænomenon which may perhaps aid us in comprehending how, in some steep isolated hills, like the Puy Chopine in Auvergne, the volcanic mass may have been uplifted, together with large fragments of the granite on which it reposed, as MM. von Buch, Le Coq, and Daubeny have held. We learn that when the new island Neokaimeni

* British Association Report for 1843.

was formed in 1707, it went on increasing irregularly, and sometimes was lowered on one side while it gained height on the other. At different periods also during the growth of the island, isolated rocks rose up in the sea at different distances from its shore, some of them appearing and disappearing at intervals. There were many evidences of eruption before a visible crater was at length formed, so that we may infer that an intumescent mass of pasty or fluid trachyte was forcing up the top of the hill, as we see lava-currents, when they meet with an obstruction, swell up because they are encased by and confined within a solid exterior, the sides of which often slope at an angle of more than 40°. The large open rents seen on the surface of the Old Kaimeni or Hira attest the distension of that island, during the injection of lava beneath it. In a word, the whole history of these central islands shows that they owe their origin to the successive and intermittent action so characteristic of volcanos, and lends no support to the hypothesis of a single paroxysmal explosion, by which either a gigantic mountain or crater can be formed at one effort. Had the denuding action of the sea never removed the central portions of the ancient cone, all those masses of brown trachytic lava and pumice which have now gone to the production of the central volcano, called the Kaimenis, would have been expended partly in the filling of fissures with melted matter, forced upwards, partly in the outpouring of lava, and ejection of scoriæ from a permanent central vent. For in some cases, as in the Sandwich Islands, we see craters much loftier than that which crowns Etna emit streams of lava of enormous volume. But it happens more commonly in volcanos, that, as they gain in height, the pressure of the central column of lava overcomes the resistance offered by the sides of the cone, so that the latter give way at some points. There can therefore be little doubt that a large proportion of the materials now composing the Kaimenis would, if the great dome had remained entire, have been emitted in the form of lateral cones. Had this occurred, the volcanic strata now encircling the Gulf of Santorin would have been intersected by veins and dikes, whereas none of the geologists who have visited Santorin make any allusion to such dikes, and Mr. Edward Forbes tells me he observed none of them in any of the three outer islands, Thera, Therasia, and Aspronisi. We must consider therefore these three masses as the basal remains of a large dome or cone, so far removed from the original centre of eruption as not to have been subject to injection from below.

As the theory of denudation requires us to suppose in the case of Santorin an oscillation of level, that is to say, first the gradual rise of a cone of submarine origin and secondly its partial submergence, it is worthy of remark that Lieut. Leycester states that on the east side of Thera there is a road now twelve fathoms under water, which formerly led from Perissa to Camari, and which was above water before the earthquakes of 1650, in which year a volcanic eruption occurred in the sea about three miles and a half north-east from Cape Colombo in Thera, where vapour and flames were thrown out and the sea was covered with pumice, and where after some months a shoal (fig. 4, A,

p. 216) was left having ten fathoms water over it. This shoal Captain Graves surveyed, and the soundings were found to deepen in all directions, demonstrating the existence of a submarine conical eminence. Lieut. Leycester was also told of houses seen at the bottom of the sea on the east of Thera, near the site assigned for the ancient Eleusis; and a similar statement was made of ruins under water, at the base of the steep cliffs of Therasia; but as on this coast inside the gulf the water deepens very suddenly from the base of the cliffs, an earthquake may have thrown down some buildings into the sea. It is therefore unsafe to draw any positive conclusion in favour of subsidence from such data.

When we reflect on the oscillations of land which have occurred within the last eighteen centuries, on the site of the Temple of Serapis near Naples, we may well imagine much greater movements of 1000 or 2000 feet to have happened in the course of the geological period during which Santorin may have been exposed to denudation.

I may observe however, that if a general upward movement should now recommence in this archipelago, so that the crater should emerge at the rate of a few feet or yards in a century, the waves would have power to tear down the rim where it is now perfect at a slight depth under water, namely between Therasia and Aspronisi and between the latter island and Thera. The same force which is now denuding the cliffs of those islands would readily undermine rocks of diversified and partly incoherent composition, during a continual change of level from century to century. The effects of this slow waste would appear in the form of wide breaches in the outer wall or ring of volcanic rocks, so that the condition of Santorin would approach much more nearly than now to the broken basaltic escarpments of St. Jago and Mauritius, as described by Mr. Darwin.

There has been some controversy as to whether the fundamental argillaceous schist seen in the south-eastern part of Thera, or the main island, crops out also in Therasia; but if so, it would not affect the theory of denudation above proposed; for we must conclude with Mr. E. Forbes that the original volcano of Santorin was formed in the bed of the Mediterranean, on which the limestone mass and argillaceous schist of Mount St. Elias, now 1887 feet above the sea, formed a submarine mountain, against which the south-eastern base of the great cone abutted. It is therefore very possible, though we have as yet no certain data for the fact, that the same pre-existing inequalities of the sea-bottom may cause similar ancient rocks to crop out in a part of Therasia.

Island of St. Paul.

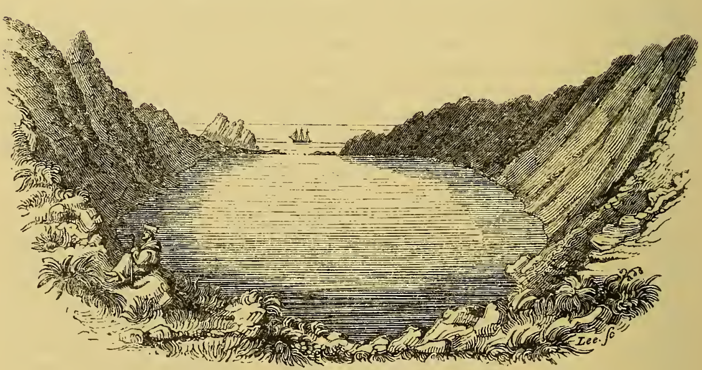
The volcanic island of St. Paul, situated in the midst of the Indian Ocean, lat. 38° 44′ south, long. 77° 37′ east, and surveyed in 1842 by Captain Blackwood, R.N., may serve in some degree to aid us in conceiving how such an archipelago as that of Santorin may have been formed (see figs. 7, 8, 9). In that portion of the volcano, probably a very insignificant part of the whole, whether in height or area, which at present emerges above the level of the wide ocean, we have a crater

Fig. 7.

Map of the Island of St. Paul, lat. 38° 44′ S., long. 77° 37′ E., surveyed by Capt. Blackwood, R.N., 1842.

Fig. 8.

View of the Crater of the Island of St. Paul.



one mile in diameter surrounded by steep and lofty cliffs on every side, save one, where the sea enters by a single passage nearly dry at low water. In the interior of the small circular bay or crater there

Fig. 9.

Side view of the Island of St. Paul (N.E. side). Nine-pin rocks two miles distant. Captain Blackwood, R.N.

is a depth of thirty fathoms or 180 feet. The surface of the island slopes away in every direction from the crest of rocks encircling this crater. The highest peak is 820 feet above the level of the sea. If we suppose considerable oscillations of level to occur by gradual movements of upheaval and subsidence, the sea which has had power to wear away part of the island and produce lofty and perpendicular cliffs, would continue to keep open the single entrance, and as it deepened it would also enter and undermine the walls of the crater, so as to widen its area. Although by this means what is now the central and higher portion of the island would be entirely destroyed, still high interior cliffs would be produced, and a section of part of the volcano, now submerged, would be laid open in the deep ravine excavated on the eastern or lower side of the island. On every other side the rim of the enlarged crater or caldera might remain unbroken.

Somma.

The evidence of Somma having been originally a submarine volcano, has appeared more and more satisfactory in proportion as recent observations have been multiplied. MM. von Buch and Dufresnoy affirm that the tuff which surrounds the mountain to the height of 1900 feet above the sea, contains marine shells analogous to those which I found at the height of 2605 feet on the neighbouring volcanic island of Ischia, all of which, except one, were of species now living in the Mediterranean. As some of the component beds of lava preserve throughout large spaces a uniform texture and are inclined at an angle of 30°, it is inferred by MM. von Buch, De Beaumont, and Dufresnoy, and probably with good reason, that they have now a much steeper slope than they had originally. On such a slope, they observe, such wide and compact sheets of lava could never have been formed. If, instead of imagining the superimposed tuffs and lavas to have swelled up like a great bubble according to the elevation-crater hypothesis, we suppose that they gained their additional steepness when they were traversed at successive periods by the dikes and veins with which they are now reticulated, we may account for the high angle of their dip, while at the same time the multitude of dikes, so far exceeding those seen at any other neighbouring point of the Phlegræan fields, points to this spot as the grand focus of eruption in ancient as well

as in modern times. It explains, in short, why Somma, like Vesuvius, towers above all the other volcanic eminences.

The summit of the submarine dome may probably have had a gentle slope on all sides, not exceeding perhaps 8° or 10°, although we have yet to learn in regard to subaqueous lavas, whether, moving through a denser and more resisting medium than the atmosphere, they may not spread in wider sheets and assume a compact texture, or an inclination exceeding that required to produce the same effects when their course is subaërial. The more general absence of ravines and valleys in the bed of the sea, where volcanic eruptions occur, would promote the spreading out of the melted matter in an even sheet, and the pressure of the incumbent water would check the expansion of the gases and prevent the mass from acquiring a more open and cellular texture. When M. Pilla had attentively observed in 1837 and afterwards in 1845 the similarity of the disposition of the beds in Somma and the modern Vesuvius, he could not resist the conclusion that both were formed in an analogous manner, and he rejected the theory of elevation-craters as applied whether to the one or the other*. At a later period however M. Pilla admitted, that a sheet of basalt 1000 metres above the sea in Somma, inclined at an angle of 24° and very compact, proved that there had been an upheaval of the mass†; an opinion which is compatible with the views embraced in this paper respecting the gradual increase of a cone by internal and external additions. That a vast number of eruptions were concentrated within a narrow space is assumed by M. Dufresnoy himself, who considers the dikes of Somma as having been the feeders of successive beds or sheets of lava. It was not overlooked that a long series of eruptions occurring within very confined limits must in the course of time have given rise to a conical mass composed in this instance of superimposed fragmentary and porphyritic beds. Such a result however was opposed to Von Buch's hypothesis, and in order to escape from it in this and other analogous cases, a very arbitrary hypothesis was resorted to;—a depression in the bed of the sea was assumed to have pre-existed, in which the beds of lava and scoriæ accumulated in horizontal masses, and the position of the mass thus formed was finally inverted, the convex side being made to project upwards instead of downwards.

Somma is the remains of a crater about three miles in diameter, the walls of which we may infer, from a passage in Plutarch, were before the great eruption of Vesuvius in the year 79, very perfect and entire, except on one side, where there was a single breach. Dr. Daubeny has shown in his comments on the passage, that when Spartacus encamped his gladiators in the crater in the year 72, Clodius the Prætor besieged him there, and keeping this single entrance carefully guarded, let down his soldiers by scaling ladders over the steep precipices which surrounded the cavity, now called the Atrio del Cavallo, where the insurgents were encamped‡. Originally therefore Somma had the usual form of craters of denudation, a single ravine interrupting the circuit

* Pilla, cited by Archiac, Hist. des Progrès de la Géol. tom. i. p. 538.
† Archiac, ibid. p. 518. ‡ See Daubeny's Volcanos, p. 216.

of the walls, and the fossa grande was perhaps a continuation of this ravine, and was hollowed out by the sea as the mountain was slowly raised above its level; but to what extent in this instance an original crater of eruption may have been widened by the sea, I will not venture to speculate.

Monte Nuovo.

MM. von Buch and Dufresnoy regard this cone and crater as consisting of solid beds of white tuff previously horizontal, which were suddenly upheaved in 1538, so as to dip away in all directions from the centre with the same inclination as the sloping surface of the cone itself. To me it appears, that in addition to all the arguments derived from the absence of rents in the walls and rim of the crater, and the uniformity of structure of the whole funnel-shaped cavity from top to bottom, we have direct historical testimony against such an hypothesis. The cone is 440 English feet high and a mile and a half in circumference, the crater within a few feet as deep as the cone is high. The dip of the beds, from 18° to 20°, is not so great as that which Mr. Darwin observed in the beds of several craters of eruption in the Galapagos Islands, where the tuffs or mud-streams are inclined at angles of from 20° to 30°*.

We have four descriptions given us by eye-witnesses, of the origin of Monte Nuovo, and there is I think no real discrepancy between them. Two of these narratives, viz. those of Falconi and Pietro di Toledo, are cited by Sir William Hamilton; another is that of Francesco del Nero, recently published (1846) in the 'Neues Jahrbuch,' and translated in the Quarterly Journal of the Geological Society for 1847, while a fourth is that officially drawn up by the physician Porzio at the request of the Viceroy of Naples.

Francesco del Nero mentions the drying up of the sea near Puzzuoli, and how the soil where the present volcanic orifice exists sank down about forty feet in the morning, and then about midday began to rise up again, so that, where it had subsided four hours before, it was elevated into a hill from which fire issued, and where subsequently a great abyss was formed. Such was the violence, the noise and the glare of light, that this eye-witness who was in his garden was much terrified. Many stones and much earth were cast out by the subterranean fire, so that they accumulated round the opening in great quantity. He then describes the shape of the hill, and finishes by referring to Porzio. Pietro Giacomo di Toledo, after mentioning previous earthquakes and a slight general rise and drying up of the bed of the sea near the coast, says that at last, on the 29th Sept. 1838, the earth opened near Lake Avernus, and a horrid mouth was seen from which were vomited furiously and with a noise like thunder, fire, stones, and mud composed of ashes. Some of the stones were *larger than an ox*. The stones went as high as a cross-bow can carry, and then fell down, sometimes on the edge and sometimes into the mouth itself. The mud was of the colour of ashes and at first very liquid, then by degrees less so, and in such quantities that in less than twelve hours

* Volcanic Islands, p. 107.

with the help of the above-mentioned stones a mountain was raised. When on the third day the eruption had ceased for a time, people looked down into the crater and saw the stones boiling up in the middle. The day after, or fourth day, the crater began to throw up again, and on the seventh much more, and some persons were knocked down by the stones and killed.

Falconi's account also alludes to the earthquake and the bursting open of the earth, and how ashes and pumice-stones mixed with water were thrown up, and how the sea retired*. Porzio says, that a large tract of land between Monte Barbaro and the sea near Lake Avernus, was seen to raise itself and of a sudden to assume the form of a growing hill, and in the night this heap of earth (*terræ cumulus*), as if opening its mouth, vomited forth a quantity of fire, pumice-stones, and ashes.

On comparing all these contemporary statements, I infer that when the ground had first sunk down on the site of the future hill, the lava gradually propelled it upwards again, so that it was distended till it burst. The force of the escaping gases then hurled into the air large fragments of the soil, mixed with mud and pumice, part of which fell back into the boiling gulf, while a part fell over the edge of the crater and contributed to the building up of the cone. We can scarcely expect to find in the walls of such a crater, any considerable remains of the beds of tuff, which after subsiding and being again elevated must have been much shattered and torn to pieces by the elastic vapours and incandescent lava shot through them. All the descriptions would lead us to refer the great mass of the hill to the ejected mud and stones, accumulated in the course of a week by the intermittent volcanic action, and I can discover nothing implying such an upheaval of previously solidified and horizontal beds of tuff, as might lead us to expect that the walls of the crater would be found to consist of that more ancient formation. Von Buch indeed is said to have found some marine shells of existing Mediterranean species, like those which occur in the tuff of Campania, in some of the beds now exposed on the edges of the crater. Such shells may have been ejected in the mud mixed with sea-water which was cast out of the boiling gulf. If however they occur near the bottom of the funnel-shaped hollow, it is possible that some fragments of the original strata which were raised and burst through by the lava and gases may remain, or some of the huge fragments cast up into the air may well be discoverable in such a position.

Since writing the above I have received a memoir on the volcanic region of Campania by Signor Arcangelo Scacchi, published in the Memoirs of the Royal Academy of Naples for 1849, in which he entirely concurs with me in rejecting the theory of upheaval for Astroni, Monte Nuovo, and other cones of that district. The position of the trachyte of the Solfatara and of Astroni are shown to be different from what they would have been had the protrusion of the trachytic masses been the upheaving cause.

In regard to Monte Nuovo, Scacchi remarks, that Porzio's account

* Campi Phlegrei, pp. 70, 77.

upon the whole corroborates the doctrine of its having been formed by eruption, in proof of which the following passage is cited from Porzio's description of the event: "Verum quod omnem superat admirationem, mons circum eam voraginem ex pumicibus et cinere plusquam mille passuum altitudine unâ nocte congestus aspicitur." Signor Scacchi also adds, that the ancient temple of Apollo, which is now at the foot of Monte Nuovo, and the walls of which still retain their perfect perpendicularity, could not possibly have maintained that position had the cone of Monte Nuovo really been formed by upheaval.

Speaking of the fossil marine shells found in the tuff of Monte Nuovo, the same geologist observes, that as the tuff of the new volcano was formed in great part out of fragments of the ancient marine, shell-bearing tuff, the appearance of such fossils is easily explained.

In one part of the circuit of Astroni he alludes to beds of ejected materials which for a short space are inclined at an angle of 40°, and which he therefore imagines may have been partially dislocated, although the materials of the rest of the same cone remain in their original position. Here I may point to the fact mentioned by Mr. Dana in his account of the Sandwich Islands, that strata of ejected substances have sometimes an original inclination of 40° in the "cinder cones," although in the "tufa cones" formed near the sea, the slope of the beds does not exceed an angle of 30°.

Etna.

The great valley on the east side of Etna, called the Val del Bove, which forms a grand amphitheatre between four and five miles in diameter, is surrounded for more than three parts of its circuit by nearly vertical precipices which vary from 1000 to nearly 3000 feet in height. As this hollow is not in the centre but on the flanks of a great conical mountain, the precipices at the upper end of the valley are the loftiest, and they diminish gradually in height towards the lower side. The original form of the lower boundary of this enormous cavity is somewhat obscured by deluges of modern lava which have passed over it; but there can be scarcely a doubt, that were these removed, the nearly circular escarpment surrounding the vast cavity would be complete, although of slight elevation on the lower or eastern side where the lavas have poured over the edge of the rampart, seeming to have scaled it, just as they passed over the walls of Catania in 1669. There seems however to have been always one point, where there was a breach in the boundary cliffs of the Val del Bove. This was situated at the south-eastern end of the valley and is called the Valley of Calanna, a narrow ravine, on one side of which perpendicular precipices 400 and 500 feet high display a succession of volcanic strata intersected by a few dikes. The Valle di San Giacomo is the continuation of the Val di Calanna, and I conceive them to stand in the same relation to the Val del Bove, which the fossa grande probably held to the Atrio del Cavallo, or which the Baranco de las angustias holds to the caldera of Palma.

After my visit to Etna in 1828, I suggested that the Val del Bove may have been produced by engulfment, an opinion which M. de

Beaumont has adopted; and he has well remarked that it could not be attributed to explosions, for in that case vast showers of ejected matter comprising the former contents of the deep gulf or valley would have been apparent on the flanks of Etna. Without denying that some part of the missing rocks may be referable to engulfment, I am now disposed to suspect that their removal may have been chiefly due to the denuding action of the sea, which probably availed itself of a breach in some lateral crater, or perhaps some partial subsidence, to gain access to and scoop out a circular bay, and carry outwards in the course of ages the debris of the undermined rocks. On consulting my notes made in 1828, I find that this was my first impression on entering the great valley; but the extent of surface covered by modern lava-streams, under which the bottom of the Val del Bove, as well as the north side of the Val di Calanna are buried, conceals so much of the ground, as to render it difficult and somewhat dangerous to speculate on the origin of the vast hollow. I may however remark, in reference to aqueous action, that although no signs have been discovered of marine shells in any beds of fragmentary matter, composing the cliffs which bound the Val del Bove, yet marine organic remains have been traced to the height of 800 feet above the sea near Trezza. Nor can there be a reasonable doubt, that if the lower parts of the great mountain were not covered with modern lava and ashes, similar proofs of the former presence of the sea would be discoverable at much greater heights. We might indeed expect to find them at a higher elevation than any of the marine tertiary strata in Sicily, and these occur in the centre of the island as high as 3000 feet above the sea. If in the vicinity of Vesuvius beds containing marine shells of recent Mediterranean species have been upraised to heights of between 2000 and 3000 feet, we are prepared to suppose that the uplifting force may have been developed with equal, if not greater intensity on the site of Etna, although no sections can be obtained in consequence of the enormous outpourings of lava and showers of scoriæ by which the older portions of the mountain are masked.

The marine strata, containing shells of recent species, which crop out along the eastern and southern base of Etna, consist in great part of volcanic materials, of tuff, scoriæ, and ashes washed down into the sea, and of rolled pebbles of lava, as at La Motta near Catania, such as the destruction of the ancient denuded parts of a great cone may have furnished. The origin of some of these may have been contemporaneous with the excavation of the Val del Bove when the cliffs encircling that valley were washed by the waves of the sea.

In reference to the question of denudation, I may ask those who have visited and may revisit Etna to consider whether the rocks called Musarra and Capra, which appear to be outstanding masses of ancient lavas intersected by dikes, rising up near the middle of the Val del Bove, are not best explained by supposing them to be remnants of the once continuous cone not entirely carried away by the waves and currents; also, whether the ridges of very ancient and crystalline volcanic rocks called Rocca Giannicola and Rocca del Solfizio, which stand

out in relief from the cliffs at the head of the great valley, have not owed their preservation to their superior hardness, and consequent power of resisting aqueous action. There are in the tertiary limestones of the Val di Noto, in Sicily, circular valleys where the steep boundary cliffs have been shaped out into a great succession of ledges, separated by small cliffs, often producing an effect which I have compared (see 'Principles,' 1st edit. 1833, p. 110, vol. iii.) to the seats of a Roman amphitheatre. The precipitous rocks of white limestone thus carved out are sometimes 500 feet high. The period of this extensive denudation was very modern, geologically speaking, and we may infer that when the sea had power to shape out such cavities in rocks of uniform solidity and compactness, it may have exerted a far greater denuding energy on such alternations of stony and incoherent materials, as those now constituting the boundaries of the Val del Bove.

The dimensions of Etna are on a sufficient scale to have produced a large crater of denudation, had a cavity been excavated in the summit or centre, instead of on the flanks of the cone. Suppose the volcanic mass not to have been cut away to a greater distance from the axis of the mountain than the middle of the Val del Bove; there might have been a cavity formed three or four miles in diameter, encircled by escarpments from 3000 to 4000 feet in height. The dikes in that case would have been most numerous in the vicinity of the original and principal centre of eruption. At the nearest point to this centre now accessible is a rock already alluded to, called Giannicola, agreeing in mineral composition with the lavas of Etna, but highly crystalline, and massive, which Hoffmann describes as almost resembling granite in structure, and between 150 and 200 feet wide. The deeper, therefore, we are enabled to see into the composition of the volcano near its central axis of eruption, the more massive and crystalline are the contents of upfilled fissures.

I have offered in the 'Principles of Geology' an explanation of the fact on which M. de Beaumont has dwelt with much emphasis, that the more ancient parts of Etna have in the course of the last 2000 or 3000 years scarcely received any superficial accessions of lava and scoriæ (see 'Principles,' 7th edit. p. 398, 1847).

The dome-shaped or conical mass was probably several thousand feet less elevated when it was originally formed. After its bodily upheaval the eruptions would become more and more lateral and basal, or in other words, the exogenous growth of the cone would shift its chief place of development. Yet the focus of eruption continued in the loftiest part of the cone where the lava still rises to a great height, and often overflows, whenever lateral eruptions occur.

Mr. Hopkins has suggested, that if the denudation of the Wealden was anterior in great part to its elevation, the removal of an incumbent weight of matter from the central area might have enabled the expansive force to act with greater intensity on that space where so much less pressure remained to be overcome. In accordance with this view, we might expect that the Val del Bove, after the abstraction of volcanic masses varying in thickness from 500 to 4000 feet, would have become

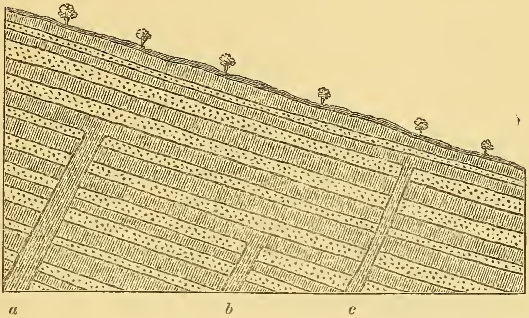
the almost exclusive theatre of eruptions. If such has not been the case, it is doubtless because the permanence of the site of habitual volcanic vents depends on deep-seated chasms and fissures in the earth's crust extending downwards many leagues, and which cannot be affected by changes of a comparatively superficial nature.

It is the opinion of M. de Beaumont, that the sheets of compact lava and alternating beds of scoriæ, which are now inclined in some of the cliffs encircling the Val del Bove at angles of 20° and 27°, were originally so horizontal that the lava emitted from different vents on the platform where they accumulated, flowed with equal freedom in every direction. To this circumstance he attributes the parallelism throughout a wide area, and the compact nature of a vast series of sheets of lava separated by more than 100 intercalated beds of pulverulent matter, cinders and angular fragments, such as are commonly cast out of craters during eruptions. The most cogent argument relied upon to compel us to embrace this view of original horizontality, is derived from the alleged fact that many of the dikes, intersecting the perpendicular cliffs alluded to, terminate upwards at different heights, and on reaching particular sheets of lava are there seen to blend, or "articulate" with them. The dikes are therefore imagined to have been feeders, or the channels by which the lava rose up from below.

The argument is ingeniously put in these terms. "Had the fluid matter been poured out on an inclined plane, the bed when consolidated would have formed an elbow with the dike like the upper bar of the letter F, instead of extending itself on both sides like that of a T (Mém. pour servir, vol. iv. p. 149), and, moreover, the series of sheets of lava would have been more numerous in parts of the mountain farthest from the axis, for all the dikes which were feeders or sources of lava would have poured their contents down the sloping cone and never upwards." Although the rectangular junctions here alluded to escaped my observation in 1828, and I have not revisited Etna since M. de Beaumont wrote his account of them, I shall take the liberty of offering a few comments on his statement of facts and method of interpreting them, as they appear to me so extraordinary that I feel at least entitled to demand, that the writer should acknowledge some difficulties in which his theory would involve us. In the first place I would ask, whence came the intercalated, incoherent and fragmentary beds? M. de Beaumont can hardly escape the inference, that they have been emitted from the same orifices as the dikes, if these last were really the feeders of sheets of lava flowing out into the atmosphere. But if the lapilli and scoriæ were cast out at the same points of eruption as the lavas, how could they possibly be of the same thickness near the vents and at a distance from them? If an even plain had existed at the commencement of these fissure eruptions, it would soon have acquired an irregular surface, for larger heaps of scoriæ would have been heaped up near the edges of the supposed linear vents, than at greater distances from them. I may also observe, that if vertical fissures gave vent originally at their upper extremities to horizontal sheets of lava so as to form dikes, joining at a right angle with the incumbent beds of lava, these dikes (fig. 10. *a*, *b*, *c*)

would be thrown as much out of the perpendicular as the beds they intersect, when the latter were tilted by subsequent movements. The dikes therefore which have been feeders ought to slope at angles of

Fig. 10.—*Volcanic Dikes.*



between 23° and 27° to the horizon, whereas in the drawing which I made of cliffs in the Val del Bove, I have represented them as nearly all perpendicular.

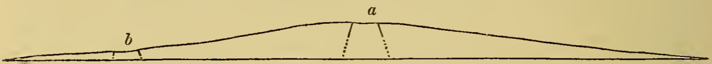
Had I seen a dike appearing to blend upwards with a sheet of lava, I should not have inferred any actual connection, unless I could have scaled the cliff, which is unfortunately inaccessible, and, hammer in hand, tested every inch of the junction. But had I thus assured myself of the fact, I should have first inquired whether the dike may not have sent off veins or branches which had penetrated between pre-existing parallel strata. If, however, I abandoned this idea as improbable because a sudden change of direction at right angles could scarcely occur or very rarely in such intrusive veins, I should have speculated on the possibility of such dikes having been filled partly from below and partly from above. After violent eruptions, the flanks of Etna have been fissured, and a bright light emitted from the rents has shown that there was incandescent lava below, although it has sometimes never reached the surface. It is conceivable, therefore, that lava-currents, descending from the higher and more central parts of the cone, might in their way fill up some rents of this kind, the tops of which are often left gaping after eruptions. Such a conjecture would at least relieve me from the extreme embarrassment in which I am placed by M. de Beaumont's hypothesis, for I am not called upon in that case to regard the dikes as the feeders of a series of uniform and parallel beds of lava, with their accompanying strata of intervening lapilli and scoriæ. The whole might then be imagined to have been poured out or projected from a permanent and powerful central vent, the eruptions being on a grand scale, so as to allow of a considerable degree of uniformity in the spreading of the materials over wide areas, on the sloping side of a great cone inclined at angles between 4 and 10 degrees. A steeper inclination may have been afterwards acquired during the distension and injection of the mountain mass.

We may naturally ask whether M. de Beaumont's notion of the existence of such linear vents as the dikes above alluded to, is borne out by the analogy of the phænomena of other active volcanos. Mr. Darwin tells me that in St. Jago he saw horizontal sections of the bases of small craters, and the mass of rock which had formed the source or feeder was of a circular, not a linear form. He has also given us the section of a cone of eruption in the Galapagos (Volcanic Islands, p. 109), where we have a most perfect natural dissection of a crater. In that case we see a series of inclined parallel beds of basalt, separated by beds of loose, fragmentary scoriæ, all parallel, and very uniform. Three of the sheets of lava unite with an irregular mass or column of the same substance, which was evidently the axis of the crater. The other streams of lava were no doubt, says Mr. Darwin, originally united to the same column, before it was worn down by the sea. Such a junction bears no resemblance to the dikes in the Val del Bove, because the lava has risen up a circular crater, and not by a linear fissure, and a cone has been formed; whereas it is precisely the absence of such small cones connected with dikes on Etna, which presents the difficulty to which I now allude.

Since the above remarks were written, I have perused Mr. Dana's valuable work, on the Geology of the United States' Exploring Expedition, published in 1849, and which reached London after this paper was drawn up. His observations on the great volcanos of the Sandwich Islands tend greatly to confirm my views, in regard to the formation of large flattened domes of volcanic matter poured out from a central vent, and they show that wide and extensive sheets of compact basalt and greystone have been formed on slopes considerably exceeding those which M. de Beaumont thought possible. In two of the principal volcanos of Owyhee, for example, Mounts Loa and Kea, we

Fig. 11.

Mount Loa, in the Sandwich Islands. (Dana.)



a. Crater at the summit. *b.* Crater of Kilanea.

have examples of huge flattened volcanic cones 15,000 feet high (see fig. 11), each equaling two and a half Etnas in their dimensions, from the summits of which, and from vents not far below the summit, successive streams of lava, two miles or more in width, and sometimes twenty-six miles long, have been evolved. They have been poured one after the other in every direction from the apex of the cone, down slopes varying on an average from 4° to 8°, but in some places considerably exceeding that inclination. Mr. Dana, indeed, convinced himself from actual observation, that, owing to the suddenness with which the lava cools, it may occasionally form on slopes equaling 25°, and still preserve considerable solidity; nay, it is even, he says, possible, from what he saw in the great lateral crater of Kilanea (fig. 11 *b*),

that a mass of such melted rock may consolidate on a slope of no less than 50° or even 60°, and be continuous for 300 or 400 feet. "Such masses are narrow," he adds, "but if the source had been more generous, it is not difficult to see that they would have acquired a greater breadth, and by a succession of ejections upon each cooled layer, even a considerable thickness might have been attained*."

The same author has also shown, that in the cinder-cones of the Sandwich Islands the strata have an original inclination of between 35° and 40°†, while in the tufa-cones formed near the sea, they have a slope of about 30°.

No one who reads the work alluded to will be of opinion, that the laws governing the formation and consolidation of sheets of basaltic or other kinds of lava have as yet been fully ascertained, or that the original inclination which they may have when flowing down the flanks of a volcanic mountain has been definitively determined by the eminent French geologist who has collected together so much valuable information on the subject.

There is another class of facts, however, brought to light by Mr. Dana's investigations, which bear directly on the rectangular junctions of dikes and streams of lava to which I have called attention in reference to the Val del Bove. He has shown, that, while copious streams of lava have been recently known to pour out from Mounts Loa and Kea from openings 13,000 feet above the level of the sea, there have been other contemporaneous fissures, produced at various elevations on the flanks of the same dome, out of which lava has streamed, unaccompanied by the ejection of any scoriæ. It appears that the lava is so liquid, that the entangled gases escape very freely from it, without casting up to great heights in the air liquid jets of the molten rock, to which volcanic dust and cinders owe their origin. Now as these rents are described as running in various directions, it is quite clear that currents of lava descending from higher points must, as often as they pass over them, give rise to junctions resembling those in the Val del Bove, though not strictly at right angles. Still it is quite necessary in the case of Etna, where we have to account for enormous masses of interpolated scoriæ, and where there has been so much viscidity in the lava, to derive the beds of fragmentary matter, as I before suggested, from a higher and more powerful and permanent central vent, for they could never have proceeded from the lateral openings or dikes without disturbing that uniformity and parallelism of the strata, on the existence of which M. de Beaumont has so emphatically insisted. It is not a little satisfactory to me to discover that Mr. Dana, with whose opinions I was previously unacquainted, has been led by his extensive examination of the volcanos of the Pacific Islands to reject Von Buch's theory of elevation-craters, although he has not alluded to the denuding action of the sea as affording an explanation of the large dimensions of many of the so-called cavities, such as Santorin, and the others on which I have dwelt in the preceding pages.

* Dana, Geol. of Amer. Explor. Exped. p. 359, note. † *Ibid.* p. 351.

Monts Dor and Cantal.

That the name of craters of elevation should have been given to large conical masses, in no part of which can any crater be discovered, whether of denudation, or engulfment, or eruption, is a singular instance of theoretical language, invented originally for distinct phænomena, becoming applied to another set of conditions, which are only in a small degree analogous. Although no craters are now discernible on the summits of Mont Dor and the Cantal in Central France, it is probable that they once possessed them, as I believe the greatest number of eruptions to have proceeded from the highest part of each mountain, where there is the greatest thickness of erupted lava and ejected matter. At this central point and around it, where so large a volume of basalt, trachyte, pumice, scoriæ, and other materials, whether solid or fragmentary, were emitted, the chief upheaval also may doubtless have occurred, and the slope of the conical mass may perhaps be greater now than it was originally. Yet as the average inclination of the dome-shaped mass of the Cantal is only 4°, and that of Mont Dor 8° 6′, we may reasonably question, after studying Mr. Dana's description of the recent additions made to the flanks of Mounts Loa and Kea, the one having a slope of 6° 30′, the other of 7° 46′, whether there is any real necessity for supposing, that the basaltic currents of the French volcanos were at first more horizontal than they are now.

The advocates of the elevation-crater theory, having assumed that the volcanic beds were in their origin almost horizontal, in Central France, found it indispensable to imagine, that a large cavity pre-existed in the granite, the lowest part of which coincided with what is now the highest part of the dome. At length, to use an expression of Ehrenberg in his paper on Volcanic Infusoria, "the concave beds were converted into a convex dome," and this as usual is referred to a paroxysmal effort of the subterranean force*.

This subject has been so ably discussed, in the controversy between MM. de Beaumont and Dufresnoy on the one side, and MM. Constant Prevost and Virlet on the other, that I need say no more on the subject. A closer observation of existing volcanos will decide whether the truth lies between the opinions of the opposite schools, and whether Messrs. Scrope, Constant Prevost, myself and others who have referred these mountains to successive eruptions proceeding chiefly from a central vent, have judged correctly, and how far we may have underrated the elevatory force, of which the intensity would no doubt be greatest at the point where the eruptive and injecting forces have been most energetic. That both the one and the other, however, have operated gradually, and with intermittent violence, not by any single great paroxysm, I feel as convinced as ever.

* Quart. Journ. Geol. Soc. vol. ii. p. 74, Memoirs.